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# Beamwidth effects on sea ice draft measurements from U.K. submarines

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ABSTRACT

Single-beam upward-looking sonars mounted on British submarines have provided a vast amount of Arctic sea ice thickness data since the early 1970s. In this paper we develop a systematic procedure to estimate the bias introduced in the measurement of the ice draft by the standard procedure of taking only the first arrival of the returned echo. Because the magnitude of this error varies significantly with the depth of the submarine, the beamwidth of the sonar and the topography of the underside of the ice, it has to be calculated for each individual transect. Based on data collected during a submarine cruise in the Arctic Ocean in the winter of 2004, we estimate that for conic beams of semi-angles 3° and 6° the observed drafts are typically 7–20% and 15–35% higher than the real drafts. In view of the size of these errors, much higher than previously reported, we argue that beamwidth corrections must always be taken into account when measuring sea ice draft from below.



## 1. Introduction

The determination of the thickness of the sea ice layer in the Arctic Ocean and surrounding seas is an essential component of the study of the Arctic climate. On the one hand, the Arctic environment and, in particular, sea ice respond quickly to global climatic changes due to amplification mechanisms that exist in the polar regions, such as the well-known ice albedo feedback. Hence, a decline in the volume of sea ice can be regarded as one of the best indicators of the warming of the planet. On the other hand, because sea ice acts as a regulator of heat and moisture transfer between the ocean and the atmosphere, changes in its thickness are likely to affect significantly the climate of the Arctic and nearby regions. Recent studies suggest that the decline of Arctic sea ice will also have an impact on the global atmospheric (Serreze and Stroeve, 2009) and oceanic circulations (Mauritzen, 2009), and, indirectly, on sea-level rise (Rignot and Cazenave, 2009) and high-latitude ecosystems (Duarte, 2008).

Prior to the satellite era, most of our knowledge of the large-scale Arctic sea ice distribution was based on submarine measurements. Analyses of data collected with upward-looking single-beam sonars during U.S. and U.K. submarine cruises in the second half of the 20th century and in the first decade of the 21st century should provide an insight on whether Arctic sea ice has been thinning. Though there are strong indications that this is indeed the case (Wadhams and Davis, 2000; Haas et al., 2008; Kwok and Rothrock, 2009), it is worth noting that comparisons between data from different cruises are not simple and may lead to inexact results if certain corrections are not properly taken into account.

This paper deals with the effects of the depth of the submarine and the finite beamwidth of the sonars used in British submarines on the measurements of sea ice draft. Our first objective is to evaluate the magnitude of such effects in different sea ice regimes. Ideally, one would then proceed to establish a procedure to extract the real draft from the directly observed draft. This is however impossible as there is not a unique real profile for a given observed profile. Thus, our second objective is more modest: we aim to develop a systematic method to estimate the average real draft over a certain transect given the average observed draft and the roughness of the observed profile.

These effects have been considered in the past. For U.K. submarines, Wadhams (1990) estimates that the corrections due to a small beamwidth (less than 5°) are of the order of 1–2% and gives a procedure to deal with wider beams (Wadhams, 1981). For U.S. submarines, the bias introduced by a finite footprint was calculated by Rothrock and Wensnahan (2007) who, based on previous work by Vinje et al. (1998), arrived at the value of $44 \pm 9$ cm.

As we shall see, analytic calculations for simple geometric profiles and numerical calculations for real profiles obtained with accurate multibeam sonars indicate that the bias introduced by the finite beamwidth of the sonars mounted on U.K. submarines may be much higher than that quoted earlier. The discrepancies between the real and the observed drafts depend on several factors including, other than the beamwidth and the depth of the submarine, the value of the real draft and the topography (or roughness) of the underside of the ice (namely the number and the shape of pressure ridges on the transect) which, in turn, depend on the location and time of the survey. As such, we argue that the subtraction of (or the multiplication by) a single overall number to extract the real draft from the observed one is an oversimplified procedure from where large errors may result.

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At a time when the Arctic is in rapid change and global warming is an active field of scientific research and a theme of passionate non-scientific debate, it is important to make sure that submarine sea ice thickness measurements include all the necessary corrections, and that their biases and uncertainties are unequivocally stated.

This paper is organised as follows. In Section 2 the reader will find a brief description of the sonar equipment used in U.K. submarines, the methods to analyse sonar records and some of the errors inherent to sonar measurements. In Section 3 we give a succinct overview of some other methods currently in use to measure sea ice thickness and highlight the poor agreement between recent thickness estimates from U.K. submarine observations and other platforms as a motivation to investigate the importance of the beamwidth effects. In Section 4 we derive analytic results for the relation between the real and the observed drafts for some simple geometric profiles so as to get an idea of the order of magnitude of the corrections. In Section 5 we consider a set of real ice profiles obtained with high-resolution multibeam sonars mounted on AUVs and simulate the measurement of the same profiles with a wide single-beam sonar. In particular, we compute the differences between the mean observed draft and the mean real draft for several values of the sonar depth and beamwidth. In Section 6 we discuss the effects of the finite beamwidth on the counting of pressure ridges. In Section 7 we introduce the concept of roughness of the underside of the sea ice, we examine its connection with beamwidth effects and describe a possible technique to evaluate the differences between the observed draft and the real draft. Finally, in Section 8 we apply the method described in Section 7 to the measurements performed during the Arctic cruise of the British submarine HMS *Tireless* in 2004.

## 2. Sea ice thickness measurements from submarines

Basin-wide measurements of sea ice thickness in the Arctic Ocean began in 1958 when the U.S. submarine *Nautilus* reached the North Pole for the first time. Since then, regular Arctic cruises by U.S. submarines have collected a vast amount of sea ice draft data, mostly in the so-called SCICEX box, which roughly coincides with the portion of the Arctic Ocean outside international waters (but includes the region north of Alaska). Most of these data sets are available through the National Snow and Ice Data Center archive (NSIDC, 2006) and have been extensively analysed by Rothrock et al. (1999, 2008).

In the early 1970s British submarines started cruising in the Arctic Ocean. For more than three decades they have been taking ice thickness data in regions rarely visited by U.S. boats, such as Fram Strait and the waters north of Greenland. Results from earlier cruises have been published in several papers (e.g. Williams et al., 1975; Wadhams, 1981; Wadhams and Davis, 2001). Wadhams (1990) provides the first evidence of the thinning of the sea ice north of Greenland. Later, he and, independently, Rothrock, observed a significant overall thinning of the Arctic sea ice by comparing results from cruises in the mid 1970s and in the mid 1990s (Rothrock et al., 1999; Wadhams and Davis, 2000).

Data from the last two Royal Navy submarine cruises, in the winters of 2004 and 2007, have been processed by the Polar Oceans Physics Group of the University of Cambridge but are as yet unpublished. Ice draft data collected by HMS *Tireless* during the March 2007 cruise acquire special relevance because they were taken in several regions of the Arctic with very different ice regimes, some of which would later become ice-free during the exceptional summer of 2007. Data indicate, for instance, that, unlike the rest of the Arctic, there was no decline in ice thickness between 2004 and 2007 in the regions north of Greenland and Ellesmere Island, which are known to have the thickest ice in the Arctic.

Since 1994 British submarines cruising in the Arctic have been equipped with two types of single-beam upward-looking sonars known as Admiralty Type 780 and Admiralty Type 2077 (henceforth AT780 and AT2077, respectively). Before 1994 only the AT780 (or one of its earlier versions, such as Admiralty Type 776) was in operation. In 2007 an upward-looking multibeam sonar (manufactured by Kongsberg Maritime) was mounted for the first time on a submarine and used to generate the first three-dimensional images of the underside of the sea ice in the central Arctic Ocean.

AT780 is an analogue device that records the full return pulse on an electrically sensitive paper roll running at constant speed. The darkness of the trace increases with the intensity of the echo and its vertical position in the paper is a function of the arrival time. As there is a range of arrival times for each emitted ping (in theory one for each wave reflected at each point of the insonified area in the bottom surface of the ice), the record consists of a dark band, as in the roll section shown in Fig. 1.

Though the entire return signal is recorded, it is common to retain only the first arrival, which corresponds to the top boundary of the dark band, or the red line in the processed roll section shown in Fig. 1 (notice that the images are “upside-down” in the sense that the top of the dark band corresponds to the bottom of the ice). This standard procedure leads to more reliable results than to averaging over the entire return pulse, and ensures compatibility with many digital systems where only the first return is recorded. Details of the techniques used to process this type of data can be found in Wadhams (1981).

In an ideal sonar with an infinitely narrow beam and with continuously emitted pings, this red line would coincide exactly with the real bottom surface of the ice. In real life such identification is not possible and we are forced to distinguish the *real draft* from the *observed draft*. In many circumstances the two may have very different values. This is a severe problem in the case of the AT780, for which the beamwidth is not given in the documentation provided by the Royal Navy but has been quoted as less than 5° by Wadhams (1990) and as 3° by Wadhams (private communication).

Once the (observed) bottom surface of the ice and the water level are identified (the latter is the blue line in Fig. 1), and the sonar range and the paper scale known, one can extract the (observed) draft as a function of time. When this is combined with the information on the position of the submarine at regular intervals, which comes in the form of separate navigation files, the final product is the ice draft as a function of the position of the submarine or the along-track distance for the entire cruise. Traditionally the track of the submarine is divided into 50 km sections. A statistical analysis of the ice draft is then performed for each section, consisting of the calculation of mean and modal ice drafts, construction of the full draft frequency distribution (usually presented in the form of histograms) and information on level ice, and pressure ridge and lead distributions.

Because a significant fraction of what we have learnt about the basin-wide Arctic Ocean sea ice thickness distribution has been derived from observations made with AT780 sonars, it is essential to know the biases and uncertainties inherent to these measurements.

The second type of sonar, the AT2077, operates in a quite different way. Results from measurements made by this sonar were provided by the Royal Navy to the Polar Oceans Physics Group of the University of Cambridge in the form of encoded files with time, position of the submarine (which comes directly from its inertial navigation system), sonar depth and calculated ice draft for each ping. Not much information is available about the specifications of this type of sonar. The beamwidth, for instance, is unknown but thought to be less than that of AT780.

We know, however, that this is a digital device that only records the first return. Thus, if $t$ is the travel time of the pulse between the moment it is generated by the transmitter unit and the moment the first return arrives at the receiver unit, $H$ is the sonar depth and $c$ is the speed of sound in the water, the ice draft is simply given by $d = H - ct/2$ (assuming that variations of $c$ with depth are negligible). Hence, with such a sonar we should be able to obtain a high-quality continuous